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Introducing AlienScenarios: a project to develop scenarios and models of biological invasions for the 21st century

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Abstract

AlienScenarios, a three-year project starting in March 2019, will evaluate for the first time the range of plausible futures of biological invasions for the 21st century. AlienScenarios consists of seven project partners and seven integrated complementary subprojects. We will develop the qualitative narratives for plausible futures of global alien species richness and impacts in the 21st century – the Alien Species Narratives

(ASNs). The ASNs further serve as overarching concept to parameterize quantitative models of global, continental and regional futures of biological invasions. We will also establish the first global mechanistic invasion model considering major processes of biological invasions such as source pools, driver dynamics and establishment rates. Further, we will assess the impacts of invasive alien species (IAS) in terms of economic costs according to the different ASNs. In addition, we will assess the consequences of different levels of implementation of the European Union Regulation on IAS. Providing some more detailed regional information, we will analyse changes of the functional composition of communities in mountain regions under different scenario storylines and will extend the analyses to the Global South using Panama as a country-level case study. Finally, the results of the other WPs will be synthesized, and the approach and results of AlienScenarios will be discussed with and communicated to stakeholders and the wider community. AlienScenarios will provide crucially needed insights for pro-active alien species management and policy. It will thus make an important contribution to global assessments and projections of biodiversity and ecosystem services, as well as regional policies (e.g. EU regulation on IAS).

Keywords
Biological invasions, global change, impacts, models, policy advice, projections, scenarios

Introduction

Human agency has modified virtually every facet of the biophysical environment (Lewis and Maslin 2015) with profound implications for the status, distribution and resilience of biodiversity worldwide (Leadley et al. 2010). Several major drivers of biodiversity loss have been identified with climate change, land-use change and invasive alien species (IAS) being among the most important ones (Secretariat of the Convention on Biological Diversity 2014). Changes in climate and land use have received much attention during the last decades, which resulted in readily available scenarios (Lamarque et al. 2005; Moss et al. 2010; Hurtt et al. 2011; IPCC 2014; Popp et al. 2016). In contrast, comparable approaches are completely missing for biological invasions despite their importance in driving biodiversity losses (Simberloff et al. 2013; Blackburn et al. 2014), and causing substantial negative impacts on human livelihoods (Pejchar and Mooney 2009). Worryingly, recent research has shown that numbers of alien species are rising unabatedly in most taxonomic groups (Seebens et al. 2017, 2018). Therefore, a thorough evaluation of plausible future trajectories of biological invasions is urgently needed to (i) enable comprehensive assessments of biodiversity changes for the decades to come, (ii) allow better-informed decisions of policy makers and stakeholders (Ferrier et al. 2016) and (iii) examine the future implications of different societal responses for biological invasions.

Objectives and approach

In AlienScenarios, we will close the knowledge gap outlined above by evaluating the range of plausible futures of biological invasions for the 21st century at different spatial scales and for a range of taxonomic groups. We will use complementary data and approaches, and examine multiple measures of impacts. We will combine the strate-

gic forward-looking methodology of scenario planning with advanced modelling approaches to construct plausible global mid-term (2050) and long-term (2100) futures of biological invasions and their impacts taking into account uncertainties. In this context, we will take advantage of several recently compiled large data sets of global alien species distributions, which have partly been compiled by members of the project team: vascular plants (GloNAF, (van Kleunen et al. 2015, 2018; Pyšek et al. 2017), amphibians and reptiles (Capinha et al. 2017), mammals (Dawson et al. 2017), birds (GAVIA, (Dyer et al. 2017), freshwater fish (Dawson et al. 2017) and selected invertebrates (ants, spiders, Bertelsmeier et al. 2013; Roura-Pascual et al. 2016; Dawson et al. 2017). In addition, we will use the Alien Species First Record Database (Seebens et al. 2017, 2018), an exhaustive database of global historic alien species accumulation rates. Finally, for regional analyses AlienScenarios will make use of complementary alien species data for in depth-analyses.

Overview of the AlienScenarios project structure

AlienScenarios consists of seven work packages (WPs) (Figure 1) that are briefly described below.

WP I: Developing global storylines and scenarios of biological invasions in the 21st century (Lead: University Vienna, Bernd Lenzner, Franz Essl)

Alien species displacement and establishment are affected by a range of drivers. These drivers have been comprehensively assessed in a workshop on alien species scenarios co-organized by three partners of AlienScenarios (F. Essl, B. Leung, N. Roura-Pascual) in Vienna in October 2016. In this workshop, an interdisciplinary panel of c. 30 experts performed an elicitation of the existing literature, and assessed relevant mechanisms and pathways. The assessment identified the seven most relevant drivers for biological invasions in the 21st century: land-use and land cover change, biodiversity change, climate change, human population development, international trade and transport, legislation, and agreements as well as scientific, technological and societal development (Roura-Pascual in prep.).

WP I builds on this preparatory work and transforms it into a conceptual framework for the development of scenarios on how alien species richness and impacts might change throughout the 21st century. Based on the subset of the seven most relevant drivers of biological invasions, we will develop internally consistent storylines – the Alien Species Narratives (ASNs) (Figure 2) – that form the core elements of our scenario framework (Rounsevell and Metzger 2010). Given that we are developing biological invasion scenarios for the first time, and thus want to explore the full range of potential future alien species trajectories, we choose a descriptive approach (Priess and Hauck 2014; IPBES 2016) to come up with four to five ASNs.

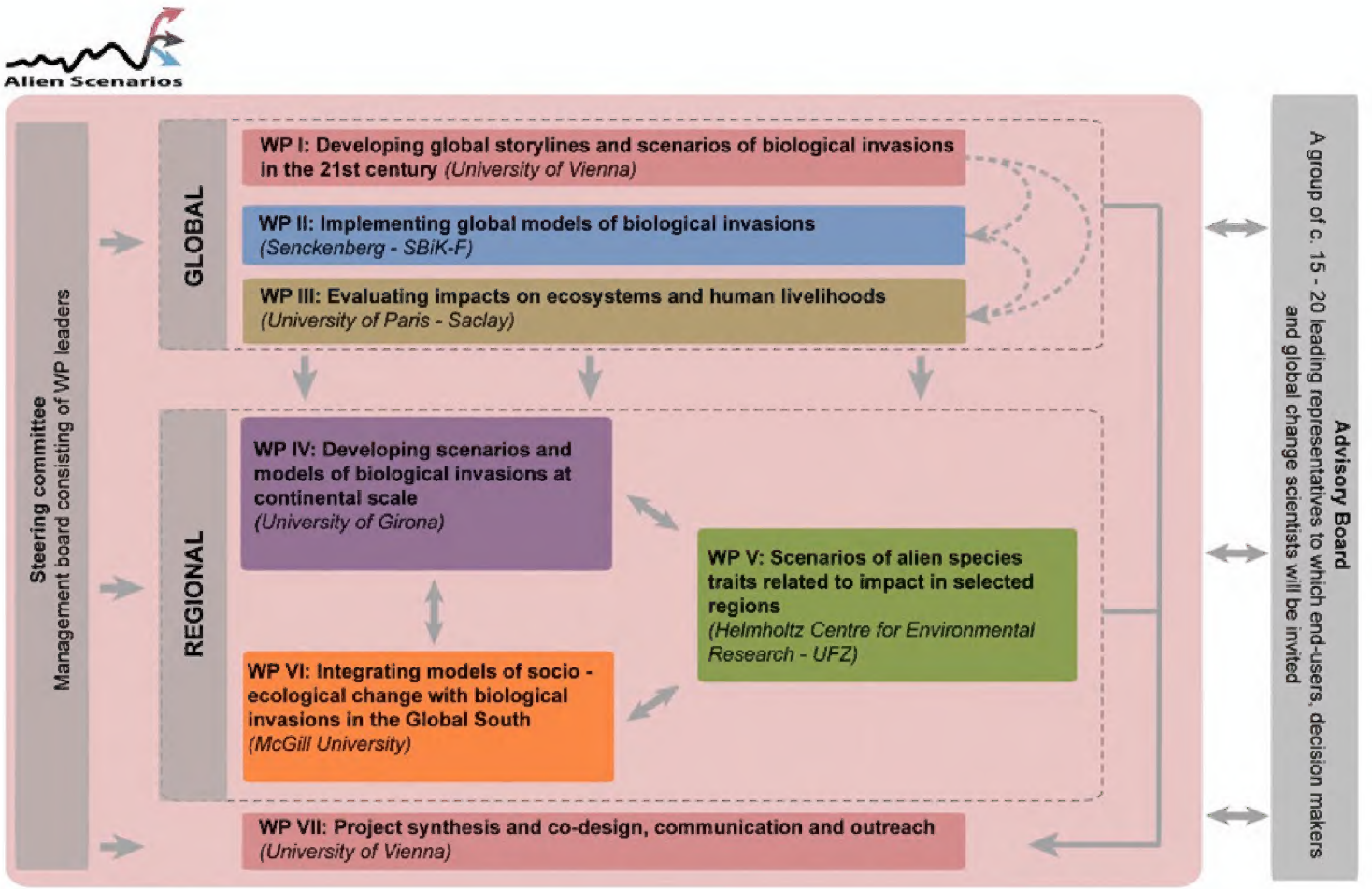

Figure 1. Project management structure and the interactions between the work packages of AlienScenarios. Shown are the seven work packages (WPs), the institution of the WP lead, the integration of the WPs within the project, the external Advisory Board, and the Steering Committee consisting of the WP leaders that is responsible for internal decision making. The arrows indicate the interconnectedness of the WPs in terms of data, idea and material exchange.

Further, we are going to construct the ASNs independent of other frameworks to ensure the greatest freedom in exploring different facets of the system more rigorously. This way we will avoid constraints held by pre-existing storylines that are likely too general for the specific needs in invasion science (Chytrý et al. 2012). The ASNs will then a posteriori be set into a broader context (see Spangenberg et al. 2012) and for example linked to the widely used Shared Socio-economic Pathways (SSPs, O'Neill et al. 2014) and Representative Concentration Pathways (RCPs, van Vuuren et al. 2011) developed for climate change research. We will follow a matrix architecture approach (van Vuuren et al. 2014) combined with a "one-on-one" mapping of the scenario narratives (Zurek and Henrichs 2007) to assess the congruence between the RCP x SSP and the ASN frameworks. This way, we will identify the relationships of biological invasions to global socio-economic and environmental change scenarios.

The ASN framework developed here will serve as the overarching concept for the simulations of the global (WP II) models of biological invasions, for assessing the global impacts that future invasions may cause (WP III), and for developing continental (WP IV) and regional alien species scenarios and models (WPs V, VI).

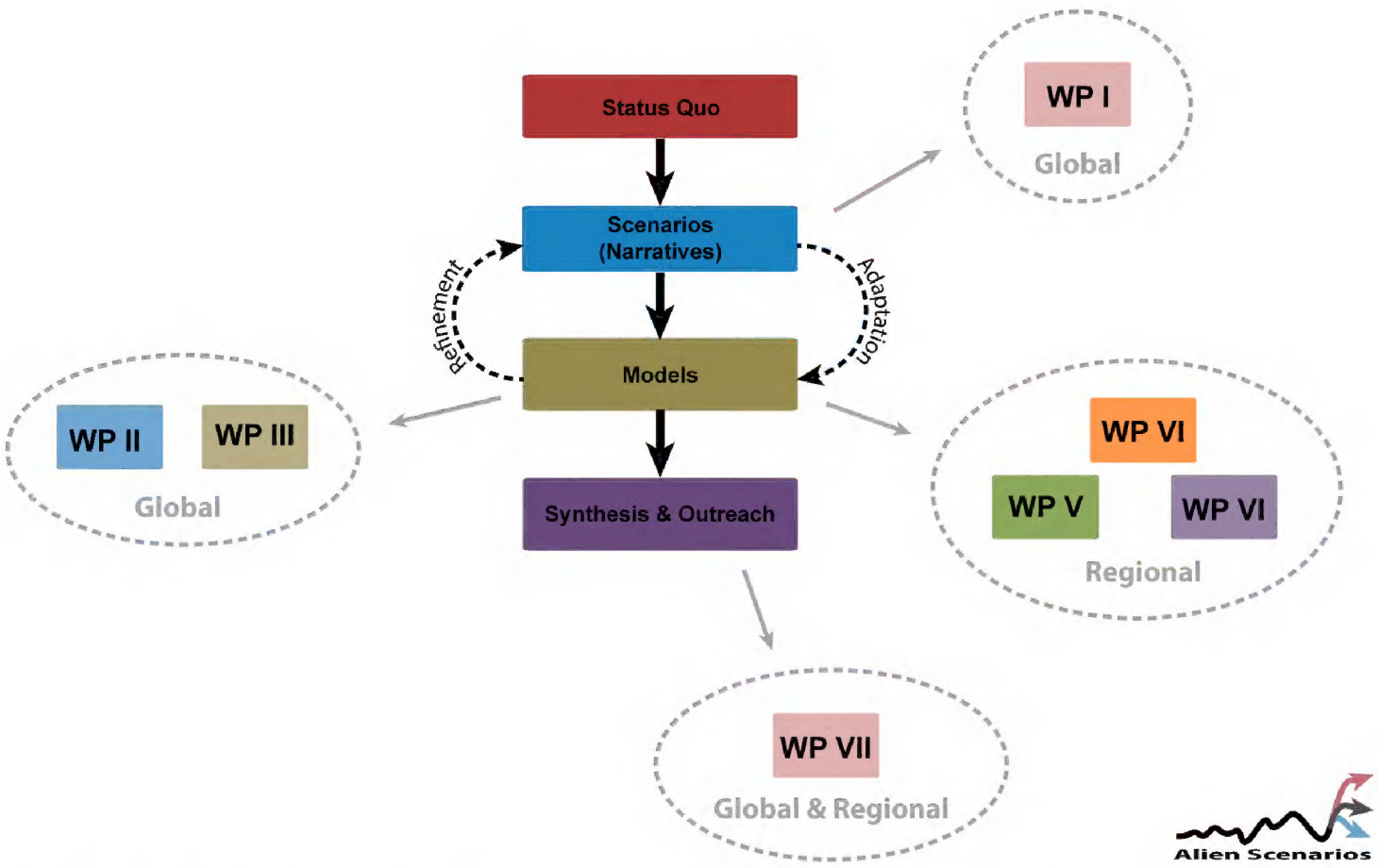

Figure 2. Conceptual figure showing the key elements and key steps for developing a framework for global scenarios (WP I) and models (WPs II, III) of biological invasions, from which continental and regional scenarios and models will be derived (WPs IV, V, VI). The figure is composed of a conceptual layer (boxes) that describes the stepwise scenario- and model-development process from initial data assessment and mobilisation to storyline construction, model quantification and, finally, to the synthesis of the full biological invasion scenarios and their communication. The position of the seven WPs of AlienScenarios along this scenario- and model-development axis is shown separately for global and regional scenarios.

WP II: Implementing global models of biological invasions (Lead: Senckenberg BiK-F, Hanno Seebens)

In this WP, a model of alien species accumulations on large spatial (global, continental) and temporal scales (centuries) will be developed and explored for various scenarios obtained from WP I. A common feature of existing invasion models (e.g. Leung et al. 2004; Costello et al. 2007; Brockerhoff et al. 2014) is that invasion dynamics were calculated based on trends of drivers such as import volumes of a country. While driver dynamics have been proven to be valuable predictors of invasion dynamics (Levine and D'Antonio 2003; Pyšek et al. 2010), it is essential to additionally consider potential constraints on the number of establishing species by the size of source pools (Liebhold et al. 2017; Seebens et al. 2018).

Here, we will combine the process-based extension of the statistical invasion model developed by Liebhold et al. (2017) with the modelling approach of Seebens et al. (2018) to estimate candidate species pools and to simulate the spread from these pools to alien ranges. The model will simulate the rate of invasion based on various drivers

of invasion, while the total number of establishments will be constrained by the size of the source pools. The implementation of ASNs into the newly developed model will require adaptations of the model structure as well as refinements of the scenarios.

The model will be evaluated against long-term trends of alien species accumulations obtained from the recently established Alien Species First Record Database, which provides regional time series (1500–2005) of invasions for >17,000 established alien species from various taxonomic groups (Seebens et al. 2017, 2018).

An invasion model as proposed here will provide the ideal tool to reach our objectives of developing future projections, as it integrates the most important mechanisms of invasion dynamics and at the same time provides a simple framework to simulate alien species accumulations for the drivers for which data are available in future scenarios. At the end of the project, we will have a set of invasion trajectories for each taxonomic group considered here, spanning the full range of potential developments for the 21st century. These results will also be used as baseline input for assessing future impacts (WPs III, V) and for discussing future pro-active policies and management options (WP VII).

WP III: Evaluating impacts on ecosystem services and human livelihoods (Lead: University of Paris Saclay, Franck Courchamp)

This WP focuses on evaluating impacts of the different global scenarios. Because the currency metrics is one that allows impact comparisons across different scales (time, space, taxonomy, category of impact, etc.), we will focus on economic costs as an output of most facets of this WP.

The WP will proceed with different, complementary approaches. The first one will use a meta-analysis of the state-of-the-art of current economic costs of IAS worldwide (in collaboration with environmental economists). This analysis will provide us with the first high-quality global map of costs, but also with a detailed description of current knowledge gaps, be they taxonomic, geographic or economic markets. These comprehensive current costs will then use the ASNs and results obtained by other WPs to assess (i) which species are likely to become (or remain) invasive in areas of interest and (ii) which areas on the globe are likely to become invaded by focal species, both for mid-term (2050) and long-term (2100) futures. The WP will focus on alien vertebrates, vascular plants and selected groups of insects (such as ants) for which the necessary global distribution data are available (e.g. van Kleunen et al. 2015, 2018; Capinha et al. 2017; Dawson et al. 2017; Dyer et al. 2017). We will then use local, current costs of selected alien species and project them to spatially explicit maps in order to obtain more quantitative estimates for different areas.

These invasion costs will be put in regards with costs of policies and biosecurity measures to provide an integrated scheme of prioritization according to the different ASNs developed in WP I. The approach will allow for evaluating and ranking different political and management options of biological invasions for the 21st century according to climatic and socio-economic scenarios, regions and possibly economic markets.

WP IV: Developing scenarios and models of biological invasions at continental scale (Lead: University of Girona, Nuria Roura-Pascual)

Based on the global ASN framework developed in WP I, we will zoom in on a continental (Europe) scale and construct scenarios nested within the global ones.

The main objective is to assess the consequences of different levels of implementation of the European Union Regulation on IAS (Regulation No. 1143/2014, EU 2014). This regulation has become the key policy tool in coordinating and improving the efforts of EU member states to combat IAS. EU member states differ in policies and regulatory histories, risk assessment tools and data availability (Sonigo et al. 2011), but the ramification this heterogeneity has on IAS is unknown (Tollington et al. 2017). We will examine regulations, management capacities and other socio-ecological factors (e.g. environmental heterogeneity, length of common borders) across EU member states, integrate these into a spatially-explicit model along with human vector movement (i.e. the primary mechanism of alien species transport and dispersion; Leung et al. 2004; Della Venezia et al. 2018).

We will statistically relate these socio-ecological constraints and human-mediated pathways of spread to the patterns of alien species establishment and impact across the EU (in collaboration with WPs II and III). We will focus on the IAS of EU concern (currently 49 species) as listed in the EU regulation on IAS (EU 2014). Our analyses will allow us to unravel the effect that differing policy implementation and capacities may have on the studied IAS in each member state. Further, since member states are interconnected by transportation and trade in goods, we will also parse out their ramifications for other member states (i.e. what is the effect of a "weak link"). We will also use this model to simulate the effect of alternative policies and capacities, based on a series of qualitative scenarios for managing IAS in Europe constructed by applying the methodology of scenario-planning following the premises of the conceptual framework. Such an integrated approach will give a scientific basis to quantitatively examine the consequences of the differing degrees of policy implementation across the EU.

WP V: Scenarios of alien species traits related to impact in selected regions (Lead: Helmholtz Centre for Environmental Research – UFZ, Ingolf Kühn)

There is a long history of analysing species traits that are related to the success of alien species (e.g. Pyšek and Richardson 2007; Küster et al. 2008). The impacts of alien species on ecosystem functions and services, though, are mediated through effect traits (Pyšek et al. 2012). Here, we will use the downscaled scenarios and model projections of the WPs I, II and IV to apply case studies on selected taxonomic groups (such as plants, birds, mammals) and regions (mountain regions).

In particular, we will extend the results from scenario development (WPs I, II, IV) to species traits, i.e. to the increase or decrease in specific traits. This means that we will not only consider the magnitude of change in terms of species richness (WPs II, IV),

but will also consider which traits will benefit or suffer under the respective scenarios. We will applying both network analyses as well as already existing trait distribution models (e.g. Kühn et al. 2006, 2009), by combining the same environmental drivers as in WP III on land use, climate (and preferably traffic/trade routes) with traits and propagule pressure to project which trait compositions to expect under different ASN assumptions (from WP II). This will allow us to analyse alien species impacts under scenario conditions by regionalization and to recognize specific context sensitivity (Kueffer et al. 2013), but also quantify uncertainties.

Because trait information is not equally available throughout Europe, we will focus with the previous analysis on ecosystems in Europe that are highly sensitive to invasions, but not yet too heavily invaded, such as mountains (Pyšek et al. 2009). Further, these systems will have strong anticipated changes in climate and land use and an increase in trade and traffic, so that a massive transformation by alien species is likely (Alexander et al. 2016). This also means that the storylines and scenarios developed in WPs I and IV need to be extended regionally. The choice of analysed systems follows a hierarchical selection strategy, especially based on good data availability in Central Europe. By acquiring more data, this can be extended to other regions. Mountain ecosystems fulfil all requirements mentioned above and will serve as a model system to start with.

To this end, we will prioritize (i) regions and, within regions, ecosystems that are more sensitive than others, and (ii) traits that are more effective than others in causing an impact onto these systems.

WP VI: Integrating models of socio-ecological change with biological invasions in the Global South: Panama as a model system (Lead: McGill University, Brian Leung)

This WP focuses on a tropical region of particular importance for biological invasions, i.e. Panama. Panama is a tropical biodiversity hotspot (Ibáñez et al. 2002) and home to the Panama Canal, one of the major gateways of inter-oceanic marine alien species exchanges (Muirhead et al. 2015). Simultaneously, Panama faces rapid economic growth (10.6% in 2011) and population growth (>40% by 2050), and highly skewed wealth distribution (17/136 in the world). These factors influence the movement of goods and people, as well as societal values and choices (e.g. land use), which in turn, can affect biological invasions. Thus, Panama is an excellent model system of developing, tropical nations. In pursuing WP VI, we complement the global (WP II) and continental analyses (WP IV) by (1) scale: analyzing an indepth country-level analysis, (2) region: focusing on a tropical region in the Global South, which are under-represented in invasion biology studies, and (3) drivers: focusing on detailed socio-ecological models.

We will connect to an ongoing initiative, the Panama Research and Integrated Sustainability Model (PRISM, see http://prism.research.mcgill.ca), which is a first-generation nationwide spatially-explicit computational model of ecological and social components of sustainability. PRISM currently incorporates sub-models for physical

processes linked to water availability and land use, and biological patterns for the bias-corrected distributions of >6000 plant species across Panama. Further, socio-economic layers are currently being developed, including urban growth of Panama City, changes in shipping through the Panama Canal over the coming decades, and connectivity, which will influence the movement of alien species. PRISM will act as a foundation on which to explore the introduction, establishment, spread and impact of alien species. In turn, WP VI will contribute a biological invasions layer to PRISM.

In particular, WP VI will integrate quantitative socio-ecological models with the drivers of invasions identified in the ASN framework of WP I. In close collaboration with WPs IV and V, we will develop national alien species storylines nested in the global ASN framework. We will apply the general scenarios of driver changes from WP I to the context-rich knowledge of Panama, and use PRISM to actually quantify the interactions between those drivers (e.g. urban growth increases by x%, resulting in y% increase of material flow and human migration, which then results in z% land-use and biodiversity change). We will use the models from WP II as the global context, within which Panama exists (e.g. how will the invasions of trading partners change introduction pressure to Panama?). We will then model how future biological invasions in Panama quantitatively flow through the country to 2050, by combining PRISM's socio-ecological outputs with invasion models.

WP VII: Project synthesis and co-design, communication and outreach (Lead: University of Vienna, Franz Essl)

This integrative WP has three closely related goals: (i) it will use a participatory approach involving the AlienScenarios project team and an external Advisory Board for ensuring strong integration and co-design of the sub-projects and for monitoring project progress; (ii) building on the results of the other WPs, it develops a synthesis of the project results which will be discussed with the Advisory Board; and (iii) it ensures that the project and its results are communicated to stakeholders and the wider community using a range of different tools and formats.

AlienScenarios has an interdisciplinary Advisory Board of ca. 20 leading representatives to end-users, decision makers and global change scientists. The Advisory Board serves several purposes: (i) to co-develop and discuss the planned implementation of project approaches and goals to maximize applicability and transferability to other relevant initiatives (e.g. IPBES, Future Earth, CBD, GEOBON), (ii) to discuss project results and their implications for alien species policies and management, (iii) to ensure that inputs and views of the wider community will fertilize the implementation of the project and (iv) to provide advice to the WPs on specific questions and problems.

The second goal of this WP is to provide a synthesis of developed methodological approaches and obtained results for different audiences. This will be done by producing (i) a leaflet (policy brief) introducing the global ASNs, (ii) a scientific project synthesis on the implications of the project results for policy making, alien species

management and science, and (iii) a short version aimed at a more general audience as a policy brief. For the scientific project synthesis, we plan to write this either as a dedicated book with an international publisher, or as a comprehensive review publication. This will also include an in-depth analysis of the advantages and weaknesses of the different model approaches in predicting biological invasions. We will also synthesise the results obtained for the different spatial scales, regions and taxa in an integrative analysis and assessment. Finally, we will apply network analysis tools developed by J. Jeschke's team to connect concepts and hypotheses that have been proposed to explain biological invasions with the scenarios (e.g. Enders et al. 2018). This will be done in a dedicated workshop hosted in Berlin in the final project year.

Outlook

The importance of scenarios on biological invasions for science, policy and biodiversity conservation

While there has recently been substantial progress in many fields in invasion science, and while in particular modelling approaches that include projections into the future (e.g. Bradley et al. 2012; Seebens et al. 2015; Early et al. 2016), the long-term dynamics of biological invasions and the impacts they cause is still understudied. In particular, there a lack of understanding the interactions of biological invasions with other drivers of environmental change, and how different policies and trajectories of drivers may modify the future impacts of invasions.

The unabated rise in alien species numbers and their impacts on nature and human livelihood have been a growing global concern, which resulted in new regulations and initiatives attempting to tackle the alien species challenge (e.g. the new EU regulation or the likely forthcoming IPBES thematic assessment of IAS, IPBES 2016). Given the substantial impacts of biological invasions (e.g. Vilà et al. 2011; Bradshaw et al. 2016), this lack of long-term projections of biological invasions and their impacts is considered an important knowledge gap (Ferrier et al. 2016). AlienScenarios will address these questions and will thus provide results of high importance for environmental planning and policy advice (e.g. IPBES, Ferrier et al. 2016; Essential Biodiversity Variables in GEOBON, Latombe et al. 2017).

The contribution of AlienScenarios to synthesis initiatives and conservation agreements

AlienScenarios aims to deliver important contributions to several high-profile initiatives on biodiversity conservation, sustainable development and knowledge synthesis. The Convention on Biological Diversity CBD (https://www.cbd.int/) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES

(https://www.ipbes.net/) are the two most prominent ones; both are crucial for formulating and advising global IAS policy, and improved information on potential long-term dynamics of alien species is highly relevant for this purpose.

On a continental level, the EU legislation on IAS (http://ec.europa.eu/environment/nature/invasivealien/index._en.htm) is one of the most ambitious laws for managing IAS worldwide. In particular, WP IV of AlienScenarios will deliver important insights on the potential impact of implementing this regulation on future alien species dynamics in Europe.

The Invasion Dynamics Network (InDyNet) (https://indynet.de) was launched 2015 and studies temporal changes in biological invasions and their impacts. It will highly benefit from the results of the AlienScenarios project. Further, a working group on "Theory and Workflows for Alien and Invasive Species Tracking (sTwist)" (https://www.idiv.de/sdiv/working_groups/wg_pool/stwist.html) has been funded by the German Biodiversity Synthesis Centre iDiv in 2018. sTwist brings together the knowledge, methods and data needed to track alien species globally and develops robust indicators for biological invasions. For elucidating the potential future trajectories of such indicators on biological invasions, AlienScenarios will deliver crucial insights.

Finally, AlienScenarios will provide results that will be useful for elucidating potential trajectories of invasions at different scales (from national to global), and for different purposes (e.g. impacts on the environment, human livelihood).

Conclusions

Formulating and applying scenarios and models of how biological invasions may unfold in the coming decades is a daunting task. AlienScenarios will be a crucial step towards this goal, but clearly, it will only be a first step on a long road to travel. Thus, future collaborative work will be needed to advance the understanding on future invasion dynamics refining and expanding the results of this project. This will need the expertise and commitment of different stakeholders ranging from scientists of different disciplines, biodiversity managers, politicians and funding institutions.

By providing the first coherent set of projections of how biological invasions may unfold in the 21st century under different storylines of human behavior, we hope that AlienScenarios will initiate a process similar to work done in the climate change research community (IPCC 2014) and that has become hugely influential.

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References

Alexander JM, Lembrechts JJ, Cavieres LA, Daehler C, Haider S, Kueffer C, Liu G, McDougall K, Milbau A, Pauchard A, Rew LJ, Seipel T (2016) Plant invasions into mountains and alpine ecosystems: current status and future challenges. Alpine Botany 126: 89–103. https://doi.org/10.1007/s00035-016-0172-8

Bertelsmeier C, Luque GM, Confais A, Courchamp F (2013) Ant Profiler – A database of ecological characteristics of ants (Hymenoptera: Formicidae). Myrmecological News 18: 73–76.

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugała A, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A Unified Classification of Alien Species Based on the Magnitude of their Environmental Impacts. PLoS Biology 12: e1001850. https://doi.org/10.1371/journal.pbio.1001850

Bradley BA, Blumenthal DM, Early R, Grosholz ED, Lawler JJ, Miller LP, Sorte CJB, D'Antonio CM, Diez JM, Dukes JS, Ibanez I, Olden JD (2012) Global change, global trade, and the next wave of plant invasions. Frontiers in Ecology and the Environment 10: 20–28. https://doi.org/10.1890/110145

Bradshaw CJA, Leroy B, Bellard C, Roiz D, Albert C, Fournier A, Barbet-Massin M, Salles JM, Simard F, Courchamp F (2016) Massive yet grossly underestimated global costs of invasive insects. Nature Communications 7: 12986. https://doi.org/10.1038/ncomms12986

Brockerhoff EG, Kimberley M, Liebhold AM, Haack RA, Cavey JF (2014) Predicting how altering propagule pressure changes establishment rates of biological invaders across species pools. Ecology 95: 594–601. https://doi.org/10.1890/13-0465.1

Capinha C, Seebens H, Cassey P, García-Díaz P, Lenzner B, Mang T, Moser D, Pyšek P, Rödder D, Scalera R, Winter M, Dullinger S, Essl F (2017) Diversity, biogeography and the global flows of alien amphibians and reptiles. Diversity and Distributions 23: 1313–1322. https://doi.org/10.1111/ddi.12617

Chytrý M, Wild J, Pyšek P, Jarošík V, Dendoncker N, Reginster I, Pino J, Maskell LC, Vilà M, Pergl J, Kühn I, Spangenberg JH, Settele J (2012) Projecting trends in plant invasions in Europe under different scenarios of future land-use change. Global Ecology and Biogeography 21: 75–87. https://doi.org/10.1111/j.1466-8238.2010.00573.x

Costello C, Springborn M, McAusland C, Solow A (2007) Unintended biological invasions: Does risk vary by trading partner? Journal of Environmental Economics and Management 54: 262–276. https://doi.org/10.1016/j.jeem.2007.06.001

Dawson W, Moser D, van Kleunen M, Kreft H, Pergl J, Pyšek P, Weigelt P, Winter M, Lenzner B, Blackburn TM, Dyer EE, Cassey P, Scrivens SL, Economo EP, Guénard B, Capinha C, Seebens H, García-Díaz P, Nentwig W, García-Berthou E, Casal C, Mandrak NE, Fuller P, Meyer C, Essl F (2017) Global hotspots and correlates of alien species richness across taxonomic groups. Nature Ecology Evolution 1: 0186. https://doi.org/10.1038/s41559-017-0186

Della Venezia L, Samson J, Leung B (2018) The rich get richer: Invasion risk across North America from the aquarium pathway under climate change. Diversity and Distributions 24: 285–296. https://doi.org/10.1111/ddi.12681

Dyer EE, Redding DW, Blackburn TM (2017) The global avian invasions atlas, a database of alien bird distributions worldwide. Scientific Data 4: 170041. https://doi.org/10.1038/sdata.2017.41

Early R, Bradley BA, Dukes JS, Lawler JJ, Olden JD, Blumenthal DM, Gonzalez P, Grosholz ED, Ibañez I, Miller LP, Sorte CJB, Tatem AJ (2016) Global threats from invasive alien species in the twenty-first century and national response capacities. Nature Communications 7: 12485. https://doi.org/10.1038/ncomms12485

Enders M, Hütt M-T, Jeschke JM (2018) Drawing a map of invasion biology based on a network of hypotheses. Ecosphere 9: e02146. https://doi.org/10.1002/ecs2.2146

Ferrier S, Ninan KN, Leadley P, Alkemade R, Kolomytsev G, Moraes M, Mohammed EY, Trisurat Y (2016) Overview and vision. In: Ferrier S, Ninan KN, Leadley P, Alkemade R, Acosta LA, Akçakaya HR, Brotons L, Cheung WWL, Christensen V, Harhash KA, Kabubo-Mariara J, Lundquist C, Obersteiner M, Pereira H, Peterson G, Pichs-Madruga R, Ravindranath N, Rondinini C, Wintle BA (Eds) Methodological assessment of scenarios and models of biodiversity and ecosystem services Secretariat of the Intergovernmental Platform for Biodiversity and Ecosystem Services, Bonn, Germany.

Hurtt GC, Chini LP, Frolking S, Betts RA, Feddema J, Fischer G, Fisk JP, Hibbard K, Houghton RA, Janetos A, Jones CD, Kindermann G, Kinoshita T, Klein Goldewijk K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren DP, Wang YP (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change 109: 117–161. https://doi.org/10.1007/s10584-011-0153-2

Ibáñez R, Condit R, Angehr G, Aguilar S, García T, Martínez R, Sanjur A, Stallard R, Wright SJ, Rand AS, Heckadon S (2002) An ecosystem report on the Panama Canal: Monitoring the status of the forest communities and the watershed. Environmental Monitoring and Assessment 80: 65–66. https://doi.org/10.1023/A:1020378926399

IPBES (2016) The methodological assessment report on scenarios and models of biodiversity and ecosystem services. In: Ferrier S, Ninan KN, Leadley P, Alkemade R, Acosta LA, Akçakaya HR, Brotons L, Cheung WWL, Christensen V, Harhash KA, Kabubo-Mariara J, Lundquist C, Obersteiner M, Pereira HM, Peterson G, Pichs-Madruga R, Ravindranath N, Rondinini C, Wintle BA (Eds) Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 348 pp.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp.

Kueffer C, Pyšek P, Richardson DM (2013) Integrative invasion science: Model systems, multi-site studies, focused meta-analysis and invasion syndromes. New Phytologist 200: 615–633. https://doi.org/10.1111/nph.12415

Kühn I, Bierman SM, Durka W, Klotz S (2006) Relating geographical variation in pollination types to environmental and spatial factors using novel statistical methods. New Phytologist 172: 127–139. https://doi.org/10.1111/j.1469-8137.2006.01811.x

Kühn I, Nobis MP, Durka W (2009) Combining spatial and phylogenetic eigenvector filtering in trait analysis. Global Ecology and Biogeography 18: 745–758. https://doi.org/10.1111/j.1466-8238.2009.00481.x

Küster EC, Kühn I, Bruelheide H, Klotz S (2008) Trait interactions help explain plant invasion success in the German flora. Journal of Ecology 96: 860–868. https://doi.org/10.1111/j.1365-2745.2008.01406.x

Lamarque JF, Kiehl JT, Brasseur GP, Butler T, Cameron-Smith P, Collins WD, Collins WJ, Granier C, Hauglustaine D, Hess PG, Holland EA, Horowitz L, Lawrence MG, McKenna D, Merilees P, Prather MJ, Rasch PJ, Rotman D, Shindell D, Thornton P (2005) Assessing future nitrogen deposition and carbon cycle feedback using a multimodel approach: Analysis of nitrogen deposition. Journal of Geophysical Research 110: D19303. https://doi.org/10.1029/2005JD005825

Latombe G, Pyšek P, Jeschke JM, Blackburn TM, Bacher S, Capinha C, Costello MJ, Fernández M, Gregory RD, Hobern D, Hui C, Jetz W, Kumschick S, McGrannachan C, Pergl J, Roy HE, Scalera R, Squires ZE, Wilson JRU, Winter M, Genovesi P, McGeoch MA (2017) A vision for global monitoring of biological invasions. Biological Conservation 213: 295–308. https://doi.org/10.1016/j.biocon.2016.06.013

Leadley P, Pereira HM, Alkemade R, Fernandez-Manjarrés JF, Proenca V, Scharlemann JPW, Walpole MJ (2010) Biodiversity Scenarios: Projections of 21st century change in biodiversity and associated ecosystem services. Secretariat of the Convention on biological Diversity, Montréal. Technical Series 50: 1–132.

Leung B, Drake JM, Lodge DM (2004) Predicting invasions: Propagule pressure and the gravity of allee effects. Ecology 85: 1651–1660. https://doi.org/10.1890/02-0571

Levine JM, D'Antonio CM (2003) Forecasting biological invasions with increasing international trade. Conservation Biology 17: 322–326. https://doi.org/10.1046/j.1523-1739.2003.02038.x

Lewis SL, Maslin MA (2015) Defining the Anthropocene. Nature 519: 171–180. https://doi.org/10.1038/nature14258

Liebhold AM, Brockerhoff EG, Kimberley M (2017) Depletion of heterogeneous source species pools predicts future invasion rates. Journal of Applied Ecology 54: 1968–1977. https://doi.org/10.1111/1365-2664.12895

Moss R, Edmonds J, Hibbard K, Manning M, Rose S, van Vuuren D, Carter T, Emori S, Kainuma M, Kram T, Meehl G, Mitchell J, Nakicenovic N, Riahi K, Smith S, Stouffer R, Thomson A, Weyant J, Wilbanks T (2010) The next generation of scenarios for climate change research and assessment. Nature 463: 747–756. https://doi.org/10.1038/nature08823

Muirhead JR, Minton MS, Miller WA, Ruiz GM (2015) Projected effects of the Panama Canal expansion on shipping traffic and biological invasions. Diversity and Distributions 21: 75–87. https://doi.org/10.1111/ddi.12260

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Climatic Change 122: 387–400. https://doi.org/10.1007/s10584-013-0905-2

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends in Ecology and Evolution 24: 497–504. https://doi.org/10.1016/j.tree.2009.03.016

Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, Bodirsky BL, Dietrich JP, Doelmann JC, Gusti M, Hasegawa T, Kyle P, Obersteiner M, Tabeau A, Takahashi K, Valin H, Waldhoff S, Weindl I, Wise M, Kriegler E, Lotze-Campen H, Fricko O, Riahi K, van Vuuren DP (2016) Land-use futures in the shared socio-economic pathways. Global Environmental Change 42: 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Priess JA, Hauck J (2014) Integrative Scenario Development. Ecology and Society 19: 12. https://doi.org/10.5751/ES-06168-190112

Pyšek P, Jarosík V, Hulme PE, Kühn I, Wild J, Arianoutsou M, Bacher S, Chiron F, Didziulis V, Essl F, Genovesi P, Gherardi F, Hejda M, Kark S, Lambdon PW, Desprez-Loustau M-L, Nentwig W, Pergl J, Poboljsaj K, Rabitsch W, Roques A, Roy DB, Shirley S, Solarz W, Vilà M, Winter M (2010) Disentangling the role of environmental and human pressures on biological invasions across Europe. Proceedings of the National Academy of Sciences of the United States of America 107: 12157–12162. https://doi.org/10.1073/pnas.1002314107

Pyšek P, Jarošík V, Hulme PE, Pergl J, Hejda M, Schaffner U, Vilà M (2012) A global assessment of invasive plant impacts on resident species, communities and ecosystems: The interaction of impact measures, invading species' traits and environment. Global Change Biology 18: 1725–1737. https://doi.org/10.1111/j.1365-2486.2011.02636.x

Pyšek P, Jarošík V, Pergl J, Randall R, Chytrý M, Kühn I, Tichý L, Danihelka J, Chrtek Jun J, Sádlo J (2009) The global invasion success of Central European plants is related to distribution characteristics in their native range and species traits. Diversity and Distributions 15: 891–903. https://doi.org/10.1111/j.1472-4642.2009.00602.x

Pyšek P, Pergl J, Essl F, Lenzner B, Dawson W, Kreft H, Weigelt P, Winter M, Kartesz J, Nishino M, Antonova LA, Barcelona JF, Cabezas FJ, Cárdenas D, Cárdenas-Toro J, Castaño N, Chacón E, Chatelain C, Dullinger S, Ebel AL, Figueiredo E, Fuentes N, Genovesi P, Groom QJ, Henderson L, Inderjit, Kupriyanov A, Masciadri S, Maurel N, Meerman J, Morozova O, Moser D, Nickrent DL, Nowak MP, Pagad S, Patzelt A, Pelser PB, Seebens H, Shu W-S, Thomas J, Velayos M, Weber E, Wieringa JJ, Baptiste MP, van Kleunen M (2017) Naturalized alien flora of the world: species diversity, taxonomic and phylogenetic patterns, geographic distribution and global hotspots of plant invasion. Preslia 89: 203–274. https://doi.org/10.23855/preslia.2017.203

Pyšek P, Richardson DM (2007) Traits Associated with Invasiveness in Alien Plants: Where Do we Stand? Biological Invasions. Springer, Berlin Heidelberg, 97–125.

Rounsevell MDAA, Metzger MJ (2010) Developing qualitative scenario storylines for environmental change assessment. Wiley Interdisciplinary Reviews: Climate Change 1: 606–619. https://doi.org/10.1002/wcc.63

Roura-Pascual N, Sanders NJ, Hui C (2016) The distribution and diversity of insular ants: do exotic species play by different rules? Global Ecology and Biogeography 25: 642–654. https://doi.org/10.1111/geb.12442

Secretariat of the Convention on Biological Diversity (2014) Global Biodiversity Outlook 4. Montréal, 155 pp.

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L,

Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8: 14435. https://doi.org/10.1038/ncomms14435

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, van Kleunen M, Winter M, Ansong M, Arianoutsou M, Bacher S, Blasius B, Brockerhoff EG, Brundu G, Capinha C, Causton CE, Celesti-Grapow L, Dawson W, Dullinger S, Economo EP, Fuentes N, Guénard B, Jäger H, Kartesz J, Kenis M, Kühn I, Lenzner B, Liebhold AM, Mosena A, Moser D, Nentwig W, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, Walker K, Ward DF, Yamanaka T, Essl F (2018) Global rise in emerging alien species results from increased accessibility of new source pools. Proceedings of the National Academy of Sciences 115: E2264–E2273. https://doi.org/10.1073/pnas.1719429115

Seebens H, Essl F, Dawson W, Fuentes N, Moser D, Pergl J, Pyšek P, van Kleunen M, Weber E, Winter M, Blasius B (2015) Global trade will accelerate plant invasions in emerging economies under climate change. Global Change Biology 21: 4128–4140. https://doi.org/10.1111/gcb.13021

Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: What's what and the way forward. Trends in Ecology and Evolution 28: 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Sonigo P, Turbé A, Berman S, Reilly K, Nyegaard H (2011) A comparative assessment of existing policies on invasive species in the EU member states and in selected OECD countries. Final report for the European Commission, DG ENV, 258 pp.

Spangenberg JH, Bondeau A, Carter TR, Fronzek S, Jaeger J, Jylhä K, Kühn I, Omann I, Paul A, Reginster I, Rounsevell M, Schweiger O, Stocker A, Sykes MT, Settele J (2012) Scenarios for investigating risks to biodiversity. Global Ecology and Biogeography 21: 5–18. https://doi.org/10.1111/j.1466-8238.2010.00620.x

Tollington S, Turbé A, Rabitsch W, Groombridge JJ, Scalera R, Essl F, Shwartz A (2017) Making the EU Legislation on Invasive Species a Conservation Success. Conservation Letters 10: 112–120. https://doi.org/10.1111/conl.12214

van Kleunen M, Dawson W, Essl F, Pergl J, Winter M, Weber E, Kreft H, Weigelt P, Kartesz J, Nishino M, Antonova LA, Barcelona JF, Cabezas FJ, Cárdenas D, Cárdenas-Toro J, Castaño N, Chacón E, Chatelain C, Ebel AL, Figueiredo E, Fuentes N, Groom QJ, Henderson L, Inderjit, Kupriyanov A, Masciadri S, Meerman J, Morozova O, Moser D, Nickrent DL, Patzelt A, Pelser PB, Baptiste MP, Poopath M, Schulze M, Seebens H, Shu W-S, Thomas J, Velayos M, Wieringa JJ, Pyšek P (2015) Global exchange and accumulation of non-native plants. Nature 525: 100–103. https://doi.org/10.1038/nature14910

van Kleunen M, Pyšek P, Dawson W, Essl F, Kreft H, Pergl J, Weigelt P, Stein A, Dullinger S, König C, Lenzner B, Maurel N, Moser D, Seebens H, Kartesz J, Nishino M, Aleksanyan

A, Ansong M, Antonova LA, Barcelona JF, Breckle SW, Brundu G, Cabezas FJ, Cárdenas D, Cárdenas-Toro J, Castaño N, Chacón E, Chatelain C, Conn B, de Sá Dechoum M, Dufour-Dror J-M, Ebel AL, Figueiredo E, Fragman-Sapir O, Fuentes N, Groom QJ, Henderson L, Inderjit, Jogan N, Krestov P, Kupriyanov A, Masciadri S, Meerman J, Morozova O, Nickrent D, Nowak A, Patzelt A, Pelser PB, Shu W-S, Thomas J, Uludag A, Velayos M, Verkhosina A, Villaseñor JL, Weber E, Wieringa JJ, Yazlık A, Zeddam A, Zykova E, Winter M (2018) The Global Naturalized Alien Flora (GloNAF) database. Ecology 100: 1–2.

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: An overview. Climatic Change 109: 5–31. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren DP, Kriegler E, O'Neill BC, Ebi KL, Riahi K, Carter TR, Edmonds J, Hallegatte S, Kram T, Mathur R, Winkler H (2014) A new scenario framework for Climate Change Research: Scenario matrix architecture. Climatic Change 122: 373–386. https://doi.org/10.1007/s10584-013-0906-1

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecology Letters 14: 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

Zurek MB, Henrichs T (2007) Linking scenarios across geographical scales in international environmental assessments. Technological Forecasting and Social Change 74: 1282–1295. https://doi.org/10.1016/j.techfore.2006.11.005